LCA Methodology

Environmental Assessment of Brownfield Rehabilitation Using Two Different Life Cycle Inventory Models

Part 1: Methodological Approach *

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Environmental Assessment of Brownfield Rehabilitation Using Two Different Life Cycle Inventory Models
Part 1: Methodological Approach – Part 2: Case Study (DOI: http://dx.doi.org/10.1065/lca2006.10.279.2)

Preamble. Brownfield rehabilitation recycles land resources in an open loop. LCA has been used in the past to evaluate the reduction in site-specific impacts and the impacts of the rehabilitation service system itself, called primary and secondary impacts in this paper, respectively. The consequences of reintroducing the site in the economy have not, however, been considered. This last has been touted as an efficient way to counter environmentally destructive urban sprawl. This article is the first of two on how a consequential model allows the inclusion of the environmental consequences of reoccupying a brownfield, called tertiary impacts in this paper. The second paper provides an actual case study.

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Abstract

Goal, Scope and Background. The primary goal of this paper is to present a LCI modelling approach that allows the inclusion of all three types of impacts. The approach is based on consequential LCA (CLCA) rather than more common attributional LCA (ALCA). In CLCA, system boundaries are expanded in order to include all significantly affected activities. In addition we show how changing from an attributional to a consequential approach alters how the impacts are evaluated, and discuss the applicability of these two distinct approaches to brownfield rehabilitation decision support. The paper is restricted to urban and contaminated brownfields that are the result of industrial use and whose rehabilitation is aimed at allowing residential redevelopment.

Main Features. The approach is based on an analogy between the open-loop recycling of material resources and brownfield rehabilitation. Brownfield rehabilitation is associated with two functions: (1) managing the legacy of past occupations on the site, analogous to a waste management function, and (2) providing redevelopable land, analogous to a commodity production function. The consequential system is expanded to cover the subsequent occupation life cycle of the brownfield and the effects on the occupation life cycles of other sites. The proposed model quantifies effects on sites competing to supply the same occupation function. Two approaches are proposed to determine the nature of the sites that are affected and to what extent they are affected: the first resembling a closed-loop approximation, and the second based on economic partial-equilibrium models.

Results and Conclusions. The scope of the CLCA is far more complex than that of the ALCA. It requires additional data that are associated with important sources of uncertainty. It does allow, however, for the inclusion of tertiary impacts, making it suitable for the evaluation of the often cited environmental benefits of reintegrating the site in the economy. In addition, the ALCA methodology seems to be inappropriate to compare brownfield management options that result in different subsequent uses of the site. Since the effects of this fate are included within the scope of CLCA, however, virtually any brownfield management option available to a decision-maker can aptly be compared. The evaluation of primary and secondary impacts also differs when the consequential approach is used rather than the attributional approach. It is impossible to anticipate the effects of these methodological differences on the results based on the qualitative discussion presented in this paper.

Perspectives. The complexity and uncertainty introduced by switching to a consequential approach is very high: it is therefore recommendable to evaluate the significance in the gain of environmental information in an actual case study to determine if system expansion is recommendable. Such a case study is presented in Part II to this paper.

Keywords: Attributional LCA (ALCA); Brownfield; Brownfield rehabilitation; consequential LCA (CLCA); contaminated site remediation; land use; open-loop recycling

1 Introduction

1.1 Background

The term brownfield originally designated sites which had previously been under occupation, as a contrast to greenfield land, i.e. land not previously used for development. Today, the term brownfield designate sites that (1) have previously been developed, (2) are presently derelict, vacant or under-utilized and (3) can only be reused if they are rehabilitated;

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Table 1: Examples of intrinsic impacts of brownfields [2–7]

	Physical state of site (including contamination)	Economic state of site (idling)
Economic impacts	Devaluation of surrounding land	Loss of economic opportunity, loss of tax base
Social impacts	Adverse impact on neighbourhood image, eyesore	Loss of employment, worsens inner-city deterioration
Environmental impacts	Potential risk to human and environmental health, impact on biodiversity and life support functions (LSF)	Loss of urban land for development, encouraging environmentally harmful urban sprawl

they often also (4) are contaminated, (5) contain infrastructure and (6) are in urban contexts [1,2]. Brownfields are intrinsically responsible for various economic, social and environmental problems (examples in **Table 1**). These stem from (1) the (physical and geochemical) state of the site, and (2) the fact that it is economically inactive.

The scope of brownfield management decisions includes (1) the choice of an appropriate final physical state of the site; (2) the choice of processes used to transform the site; and (3) the choice regarding the desired subsequent fate of the site. These decision issues are interrelated. Indeed, redevelopment cannot occur without prior management of legacy, and, unless legally constrained to do so, the site will probably not be rehabilitated unless its redevelopment is expected. Also, the two functions are technically co-dependent: the management of the legacy depends on the requirements posed by the planned subsequent fate, while the subsequent use of the site is limited by the post-intervention state of the site (suitability for use).

This paper focuses on brownfield rehabilitation, i.e. brownfield management that deals with the physical legacy on the site (possibly including contamination) in a way that allows the site's reentry in the economy, to be used for e.g. industrial, commercial or residential purposes. Previous studies suggest that reinserting brownfields in the economic cycle effectively displace economic activity from periurban greenfields to urban sites, curbing socially, economically and environmentally undesired urban sprawl [2–7].

The intrinsic environmental impacts of contaminated sites have been a decision issue for decades for site management. Recently, authors have underlined the importance of accounting for a wider scope of issues to ensure that site management is sustainable [8–11]. Authors in the field of contaminated site remediation have brought attention to the environmental impacts of the remediation itself (see e.g. [10,12,13]). Authors in the field of brownfield management have, on their part, stressed that issues relating to contaminated site management and spatial planning should be dealt with in an integrated way [8,10,11].

A typology has been proposed by which 'primary impacts' represent the impacts associated with the state of the site and 'secondary impacts' refer to the life cycle potential impacts of the actual site rehabilitation [13–16]. Several LCAs have assessed secondary impacts of contaminated site remediation [17]. Other activities of site rehabilitation (e.g., infrastructure management) are usually excluded, although at least one exception exist [18]. Primary impacts are difficult to assess with LCA since they are strictly site-specific and not functionally determined. Nonetheless, they have been accounted for in some site-remediation LCAs (e.g. [13,15,19]).

No LCA has accounted for the fate of brownfields after rehabilitation. The impacts associated with the fate of the site are in this paper called 'tertiary impacts'.

Two types of LCA have been distinguished attributional LCA (ALCA), which can assess the burdens of a product life cycle and its subsystems; and consequential LCA (CLCA), which aims at describing the technosphere-wide effects of changes within a product life cycle [20]. Previous studies can best be described as ALCAs. Since both provide different types of information, it may be relevant to see how both can be used to generate environmental information to support a brownfield management decision.

1.2 Aims

The principal aim of this paper is to show how CLCA can, through system expansion, yield useful information on tertiary impacts. The paper also aims at showing how the choice between CLCA and ALCA leads to differences in assessing primary and secondary impacts and how the resulting CLCA and ALCA models differ in terms of applicability to different decision contexts. Our presentation of the methodology focuses on the case where a contaminated urban brownfield resulting from industrial occupation (in the following denoted the 'tracked site') is rehabilitated for residential redevelopment. The methodology can easily be generalised to be valid for a wide range of brownfield management cases.

2 Methodology

2.1 Brownfield rehabilitation as open-loop recycling of land

The premise underlying the proposed methodology is that brownfield rehabilitation is analogous to material recycling, and that consequently, LCI methods used for recycling processes may be, to a certain degree, adapted to rehabilitation activities. This analogy is presented in **Fig. 1**, which shows the life cycle stages of a material resource (a metal) and delimited amount of land resources (a site). The metal is included in successive product life cycles, whose functions are associated with the use phase of the products (fat arrow). In each life cycle phase, part of the metal can be lost to landfills or to the ecosphere. Similarly, a site will be recycled to successive occupation life cycles, whose functions occur during the occupation phase. At the end of this phase, the state of the site sometimes allows for direct reintroduction in the economy. In other cases, it is reintroduced after rehabilitation. Decision-makers can also choose interventions other than full-out rehabilitation to managed brownfields (e.g. minimal risk management). Finally, land is subject to natural processes that tend to reintegrate sites in the ecosphere: renaturation for abandoned sites and natural attenuation for contaminated sites.

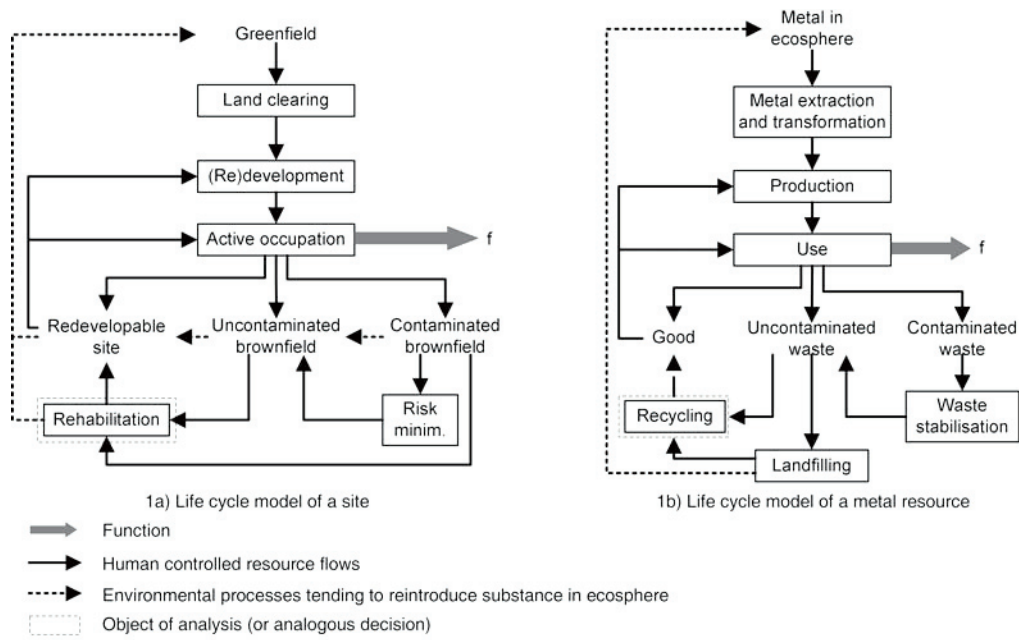

Fig. 1: Illustration of the parallel between land and material recycling

Recycling and rehabilitation both provide (1) a waste management function, associated with the input of a degraded resource from the previous product/development life cycle, and (2) a resource production function, associated with the output of upgraded resource into the subsequent product/occupation life cycle. A distinction is made between closed-loop recycling, where a resource is recycled back into the product system from which it originated, and open-loop recycling (OLR), where the resource is recycled into other product systems [21]. In the case at hand, brownfield rehabilitation is considered OLR since the previous (industrial) and subsequent (residential) site occupations differ.

2.2 Attributional scope of rehabilitation systems

The purpose of ALCA is to provide information concerning the environmental properties of an investigated life cycle and of its subsystems [22,23]. Therefore, the analysed system is limited to the life cycle of the brownfield rehabilitation only: the life cycles of the products and energy carriers needed to provide the rehabilitation function. Effects on other stages of the site's life cycle and on other sites are outside the attributional system's scope. The resulting system can be described as a 'waste-to-gate' system.

The time horizon is equal to the rehabilitation time, which may vary widely. For example, rehabilitation by 'excavation and disposal' is usually much shorter than one involving *in situ* bioremediation. The time-horizon should also logically cover offsite activities directly caused by the rehabilitation (e.g. offsite decontamination of soil). If the future emissions of contaminants that were not degraded are to be taken into account (e.g. leaching of contaminants from landfilled soil), the time-horizon can be expanded quite drastically, possibly to the 'hypothetical infinite time-horizon' [24].

2.3 Consequential scope of rehabilitation systems

Consequential LCA of brownfield rehabilitation should provide information on the environmental consequences of the rehabilitation service system. The system should include the processes where the most important consequences occur. A CLCA of material recycling accounts for processes affected by changes in the flow of material recycled both into and from the investigated system [25]. Changes in the flow of recycled material into a product system can displace other types of waste management options (e.g. landfilling) and may reduce the amount of recycled material used in other product systems [25]. An increase in the flow of material from a recycling process replaces the use of other substitutable materials.

A similar approach is used to investigate the effects of brownfield rehabilitation. Brownfield rehabilitation displaces other options for the management of the tracked site. If an intervention on the site is not required, the avoided option may simply be further idling of the site. If intervention is required because, for example, the contamination poses a significant risk, the avoided brownfield management option is not necessarily obvious and should be specified by the decision-maker. If, after rehabilitation, the tracked site is used for housing, the housing services provided at the tracked site (f^*) can affect the quantity of housing services provided through the use of other sites (f^o) (variables concerning the tracked site and other sites are identified by the exponents * and ^{o}, respectively).

The environmental impacts of material recycling depend on what material is replaced by the material from the recycling process. It is often assumed that this recycled material replaces virgin material of the same kind, but it may displace virgin or recycled materials of the same type or completely different materials [26]. Similarly, the tertiary impacts of

brownfield rehabilitation depend on what other sites are affected. In the brownfield literature, it is usually implicitly assumed that rehabilitated brownfields compete directly with suburban greenfields. Some studies go so far as explicitly stating that for every project taking part on a brownfield, the same project is avoided on greenfields (e.g. [5]). This is the mechanism by which rehabilitation is assumed to curb urban sprawl. However, the rehabilitation of a brownfield can affect the use of a wide variety of sites: greenfields, vacant redevelopable sites, other occupied sites, and other brownfields. Relevant aspects of the affected sites include (1) the site type; (2) the site's context; and (3) the site's location. The type of site will directly affect the burdens of preparing the land for development (e.g. greenfields will likely need to be cleared prior to development). The context of the site will affect the development phase (e.g. infrastructure requirements, functional efficiency). Since the infrastructure will be different for different contexts, the burdens of the occupation phase are also affected. The location of the site will affect all life cycle phases through, e.g., transport distances.

2.4 Assessing primary impacts

Both ALCA and CLCA should ideally account for changes in site contamination and the physical state of the site (e.g. landscape and geohydrologic characteristics) that result from the rehabilitation. These impacts are by their very nature very site-specific and therefore difficult to assess using LCA. We suggest here that existing LCA methods at the disposal of the practitioner can be used to provide proxies for these impacts. The reliability of these proxies will be diminished compared to using site-specific indicators, as was done, for example, by Beinat et al. in the REC method [12] for contamination-related risk reduction and by Diamond et al. [27] for impacts associated with the physical state of the site. However, these proxies have the advantages of being easy to calculate and to be directly comparable with other impacts measured in the LCA.

For primary impacts associated with site contamination, we suggest that the site contaminants are simply entered in the inventory as 'emissions to soil', as was done in one site remediation LCA [13]. For primary impacts associated with the physical attributes of the site, we suggest that land use impact assessment methods used in LCIA [28], for example based on effects on life support functions and biodiversity, can be used.

Accounting for primary impacts in the consequential model involves two additional aspects:

(1) While in the attributional model, primary impacts of the investigated rehabilitation option are implicitly compared to a status quo scenario, in the consequential model they are compared to an alternative brownfield management option, which may or may not be the status quo.

(2) Since the subsequent occupation life cycle is included within the scope of the study, the primary impacts of the redevelopment and reoccupation phase should be included. If the rehabilitated site is used for residential buildings, these phases are unlikely to significantly affect site contamination level. However, it may be relevant to account for impacts related to the physical state of the site. During the development phase, transformation impacts may be important if the state of the site is further modified. For the occupation phase, land occupation impacts (i.e. the impacts of keeping the site at an environmental quality level lower than its renaturation potential) may be significant. Again, it is the comparison between the investigated and the avoided land occupation that is of interest. Land occupation impacts are especially relevant if the site is kept in completely different states after the brownfield management stage (e.g., revegetated brownfield vs. continuous residential redevelopment).

2.5 Assessing secondary impacts

The attributional model includes the brownfield rehabilitation and the life cycle of the products, materials and energy carriers required for the rehabilitation. The rehabilitation activities can include risk, infrastructure and landscape management. The burdens of multi-functional processes (e.g., recycling of material from dismantled infrastructure) are allocated between the rehabilitation function and other life cycles using appropriate allocation methods.

The consequential model should account for processes affected by brownfield rehabilitation, whether these are part or not of the rehabilitation life cycle. Multi-functional processes are dealt with using system expansion (activities that are significantly affected by the recycling of material from brownfield infrastructure should, for example, be included). Also, the use of constrained production factors in the rehabilitation life cycle and their alternative uses should be identified [25]. Examples of constrained production factors in the field of rehabilitation can include regionally constrained landfill volume, constrained soil decontamination processes and limited grants for brownfield interventions. The consequential model should also account for the avoided activities of the alternative brownfield management option.

2.6 Assessing tertiary impacts

The scope of the tertiary impacts includes the subsequent development and occupation of the site as well as affected life cycles of other sites. They are accounted for in the CLCA only. Temporal boundaries are very important since the burdens of the sites' fates are a function of time. The time should ideally reflect the total life-expectancy of the new houses. This type of value is considered quite subjective, however, and normally has no real relation to the time the buildings will actually be used [29].

As stated above, the tertiary impacts of brownfield rehabilitation depend on the type, context and location of other sites that are affected by the rehabilitation. In our method this complexity is reduced because we only consider two site types: vacant urban sites and suburban greenfields. The method is based on further simplifications:

- It does not take into account effects on the regional functional efficiency of land. The quantity of housing services supplied by a site Δf is given by $\alpha\Delta X$, where ΔX is the land area rehabilitated and α is the functional effi-

ciency of the site, i.e. the amount of housing services provided by 1 unit area of the site. Cheaper land lowers the incentive for compact development. This may result in decreasing regional functional efficiencies, i.e. less services provided per km². It is assumed here that the functional efficiency of each type of site is unaffected by the rehabilitation.

- It does not take into account effects on the total regional demand for the occupation function. Cheaper land may incite developments that would otherwise not have occurred in the region. This could have the effect of increasing the total amount of land that is under occupation in a region. This type of effect is also excluded by supposing the regional demand for the occupation function constant (ceteris paribus: $\Delta f^o = \Delta f^*$).
- It assumes that the total number of houses regionally being built is unaffected by the redevelopment of the tracked site. This reflects the assumption often made in urban spatial theory that the actual stock of houses is dependent on the growth in population [30]. It follows that the average housing services supplied by new houses on the tracked site and avoided houses on affected sites have the same average housing services output.
- Rehabilitation of the tracked site may reduce the rehabilitation of other sites if, for example, rehabilitation depends on limited public financing or if rehabilitation technologies are constrained. On the other hand, a successful rehabilitation may incite or encourage other rehabilitations by e.g. validating a remediation technology or simply by showing that such endeavours can be profitable. Such 'success stories' are often used by agencies to promote brownfield rehabilitation (see e.g. [5,31]). These effects are excluded from our quantitative model because of unreasonable uncertainties engendered in estimating them.

When it is assumed that rehabilitated brownfields compete with suburban greenfields only, we can still account for the fact that the functional efficiency varies between site types. A land use areal differential (AD), representing the ratio between the area of greenfield land that avoids development (ΔS_{GF}) and the area of brownfield redeveloped (ΔX), can be calculated by:

$$AD = \frac{\Delta S_{GF}}{\Delta X} = \left(\frac{\alpha^*}{\alpha^o_{GF}} \right)$$

This areal differential for residential development is estimated at 5.57 in North America [6]. The average distance of these suburban greenfields can also be estimated and accounted for in the assessment of the tertiary impacts. Alternative occupation of the greenfields should also be accounted for. Our method accounts for the fact that brownfield rehabilitation can affect the use of urban as well as suburban sites. It is loosely based on an approach to open-loop recycling of material that account for the fact that recycling of material from a life cycle can replace virgin as well as recycled material from other life cycles [32]. Basically, this type of model is based on the concept of equilibrium between supply and demand. For a market with an initial demand D and supply S, a supplementary supply ΔX affects the price (P) of the good and results in a new equilibrium. As long as the perturbation can be considered marginal (e.g. ΔX<<S), the effects on supply and demand can be described using the price elasticity of demand (η_D) and of supply (η_S), which quantifies how the demand and supply are affected by a change in the price:

$$\eta_S = \frac{\Delta S/S}{\Delta P/P} \quad \text{(typically above zero)}$$

$$\eta_D = \frac{\Delta D/D}{\Delta P/P} \quad \text{(typically below zero)}$$

The effects, ΔD and ΔS, of the supplementary supply ΔX in this simple partial-equilibrium model can be calculated as follows [32]:

$$\Delta D \approx \frac{\Delta X\, \eta_D}{\eta_D - \eta_S}$$

$$\Delta S \approx \frac{\Delta X\, \eta_S}{\eta_D - \eta_S}$$

The first step in our approach is to consider an urban housing services submarket (**Fig. 2**). The increase in the amount of urban housing services associated with rehabilitation (Δf^*) will reduce the market price for urban housing services. Consequently, the demand for urban housing services is positively affected $\left(\Delta f^{total}_{urban} > 0\right)$ while the supply from other urban sites is negatively affected $\left(\Delta f^{o}_{urban} < 0\right)$. Since the urban demand increases but the regional demand remains the same, some suburban occupation is avoided, i.e. $\Delta f^{total}_{suburban} = -\Delta f^{total}_{urban} < 0$.

We assume the perturbation to be marginal (i.e. $\Delta f^* << f^{total}_{urban}$). The effects can therefore also be considered marginal and may be estimated using economic partial-equilibrium models. Values for the relevant price elasticities, taken from literature reviews on the subject [30,33], are presented in

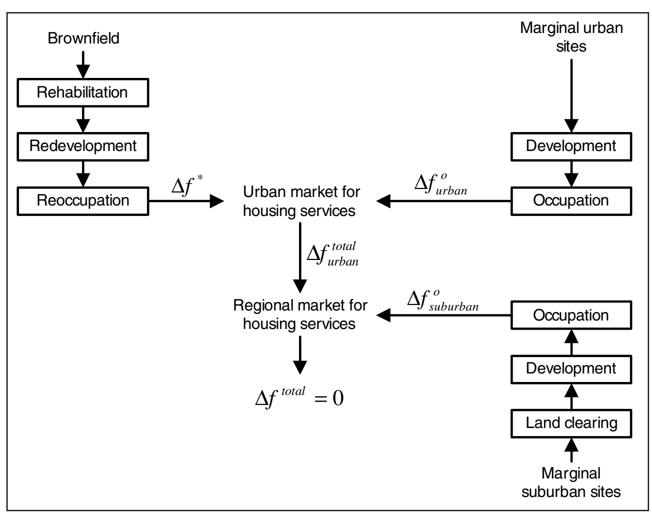

Fig. 2: Subdivision of the region in urban and suburban markets for housing services

Table 2: Values for price elasticities of demand and supply for housing services

Price elasticity of supply (η_S), surveyed by DiPasquale [30]	
Perfectly elastic	Muth (1960); Follain (1979)
Perfectly inelastic	Stover (1986)
0.3 to 0.7	DeLeeuw and Ekamen (1971)
4 to 13	Malpezzi and Maclennan (1996)
0.5 to 2.3	Poterba (1986)
3 (long run)	Topel and Rosen (1988)
1.6 to 3.7 (long-run)	Blackley (1999)
Price elasticity of demand (η_D), surveyed in Zabel [33]	
–0.3 to –0.9	Mayo (1981) – Based on family-worker's budgets
–0.67 to –0.76	Mayo (1981) – Based on housing production functions
–0.53	Mayo (1981) – Based on hedonic price index
–0.2	Mayo (1981) – Based on Housing Allowance Demand Experiment
–0.5 to –0.8	Ermisch et al. (1996)

Table 2. For the purpose of this study, the values retained are of –0.65 for the elasticity of demand for urban housing services (η_D) and 3.0 for that of supply (η_S).

The equations of the economic partial-equilibrium model are given by **Table 3**. To be applied, these relations of course require that the price elasticities of urban housing services are known or can be estimated. The area results presented in Table 3 are based on the assumption that the functional efficiency is the same at different urban residential sites, and 5.57 times that of suburban residential sites [6].

3 Discussion

3.1 System definition, data requirements and uncertainty

Using CLCA to assess rehabilitation decisions results in a system that is much larger than the corresponding ALCA system. In fact, the ALCA system consists of one life cycle phase of one site, while the CLCA consists of five life cycle phases for the tracked site as well as numerous life cycle phases for other affected sites. This greatly increases data requirements. Actual LCI data of these other life cycle phases are readily available: many LCA have been conducted on housing (see e.g. [34,35]), and the ecoinvent database contains LCI data for many types of public infrastructure (e.g. sewers [36], road infrastructure [37]).

Data uncertainty for evaluating tertiary impacts of brownfield rehabilitation is high. First, the identification of which type of sites can be marginally affected is inherently region-specific. Second, determining the types of houses and public infrastructures that are situated at these sites is difficult. Third, the data on price elasticity of housing services is quite uncertain [30,33]. Finally, the concept of housing service, central to the model, is an abstract concept that is difficult to measure in reality [33,38].

The method also presents important model limitations. First, the ceteris paribus assumption for housing services excludes possible effects on regional supply and demand. Also, the exclusion of effects on regional functional efficiency and on the rehabilitation of other brownfields also introduces uncertainty. Other solutions could have been proposed by e.g. subdividing the housing services market differently (e.g. housing services supplied from single-family houses vs. from leased apartments).

These uncertainties behove the modeller to (1) conduct sensitivity analysis accounting for different effect scenarios, and (2) to include the effects only if they are significant. This second point cannot be determined without conducting an actual brownfield rehabilitation CLCA.

3.2 Comparison with other brownfield management options

Rehabilitation for residential redevelopment is one of several brownfield management options: decision-makers can possibly also decide to rehabilitate the site for other types of redevelopment: commercial, industrial, etc. They can also decide to intervene on the site in a manner that does not allow any redevelopment (e.g. minimal intervention for risk management). Finally, they may decide to rehabilitate a brownfield and reintroduce the site in the ecosphere (assisted renaturation). The consequential methodology presented above can be used to evaluate any of these other options. For rehabilitations with site fates other than residential redevelopment, the exported function obviously should change. The assump-

Table 3: Effects on urban and suburban sites based on the market subdivision approach

Site type	Effect on demand/supply for housing services		Effect on area occupied	
	Expression	Estimated value (%)	Expression	Estimated value (ha/ha)
Other urban vacant redevelopable sites	$\frac{\Delta f^{o}_{urban}}{\Delta f^{*}} = \left(\frac{\eta_S}{\eta_D - \eta_S}\right)$	–82.2	$\frac{\Delta S^{o}_{urban}}{\Delta X} = \left(\frac{\alpha^{*}}{\bar{\alpha}^{o}_{urban}}\right)\left(\frac{\eta_S}{\eta_D - \eta_S}\right)$	–0.82
Total urban sites	$\frac{\Delta f^{total}_{urban}}{\Delta f^{*}} = \left(\frac{\eta_D}{\eta_D - \eta_S}\right)$	17.8	$\frac{\Delta S^{total}_{urban}}{\Delta X} = \left(1 + \left(\frac{\alpha^{*}}{\bar{\alpha}^{o}_{urban}}\right)\left(\frac{\eta_S}{\eta_D - \eta_S}\right)\right)$	0.18
Suburban greenfields	$\frac{\Delta f^{o}_{suburban}}{-\Delta f^{*}} = \left(\frac{\eta_D}{\eta_D - \eta_S}\right)$	–17.8	$\frac{\Delta S^{total}_{suburban}}{\Delta X} = -\left(\frac{\alpha^{*}}{\bar{\alpha}^{o}_{suburban}}\right)\left(\frac{\eta_D}{\eta_D - \eta_S}\right)$	–0.99

tions and simplifications used for the residential redevelopment case may also need to be revisited. For management options where the site is not to be redeveloped, tertiary impacts only concern the difference between the actual and the avoided fates of the site. No other sites are affected.

Attributional methodology only considers the brownfield management phase itself. Since, as was shown, the subsequent reoccupation of the site has environmental consequences, this approach is not appropriate to evaluate brownfield management options resulting in different site fates.

4 Conclusions

Presently, LCA of site rehabilitation have all been of the attributional type, and the exported 'land production' function has been excluded. This paper showed that this exported function can have environmental consequences by affecting the life cycle of other sites. Although these effects are not quantified in this paper, the literature on brownfield rehabilitation stresses that these tertiary impacts may be very important and negative (i.e. good for the environment). As for reductions in primary impacts associated with rehabilitation, tertiary impacts may help offset and possibly annul the impacts of the actual rehabilitation phase.

The switch to CLCA also changes the manner in which primary and secondary impacts are evaluated. Primary impacts associated with the subsequent occupation life cycle are included within the scope rather than just transformation impacts of the actual rehabilitation stage. Secondary impacts include avoided brownfield management options and consider only activities actually affected by the service system. These will obviously change the results of such an analysis.

Attributional LCA remains appropriate for decision-makers wanting to evaluate the environmental impacts only directly attributable to the considered rehabilitation activities. This type of LCA could be relevant for e.g. a subcontractor commissioned carry out a rehabilitation. In this case, the aims of the rehabilitation for subsequent redevelopment are exogenously determined, and restricting the analysis to the rehabilitation life cycle phase is appropriate.

If the decision-maker has a say on the site fate, however, the consequential methodology presented above is more appropriate. Concentrating on the rehabilitation phase conveys very partial information on the actual consequences of the decision. This may lead to unsound decisions. For example, minimal intervention for risk management may have negligible secondary impacts compared to a full-fledged rehabilitation for residential redevelopment. Using ALCA would therefore tend to indicate that the first option is environmentally preferable. If tertiary impacts are negative and important for the rehabilitation option, however, the minimal intervention option may be sub-optimal.

5 Perspectives

5.1 Allocation to specific occupation life cycles

This paper has concentrated on the evaluation of impacts associated with brownfield rehabilitation itself. This site life cycle phase, however, does not occur in isolation but rather is part of two occupation life cycles: the one that generated the brownfield, and the one that will utilise the brownfield as a source of land for a development project. The burdens of rehabilitation can therefore be relevant for LCA that include either of these occupation life cycles.

In an ALCA, this results in an allocation problem, where the burdens of rehabilitation must be allocated to the 'legacy management' function (associated with the previous occupation life cycle) and the 'redevelopable land production' function, associated with the subsequent occupation life cycle. The allocation problem may first be reduced by allocating specific rehabilitation activities to one or the other function: for example, removal of contaminants may be considered to be directly attributable to the previous occupation life cycle and landscaping activities to the subsequent occupation life cycle. The remaining rehabilitation activities may need to be allocated according to physical or economic relationships. One alternative is to allocate based on the economic value of the two functions of the rehabilitation, although the intrinsic interdependence of both functions makes this difficult. Another alternative, at least in theory, is to identify the point in the rehabilitation process where the worth of the site is positive (worth of rehabilitated site – cost of remaining rehabilitation activities > 0). Impacts that occur before that point are allocated to the previous occupation life cycle, and the rest are allocated to the subsequent life cycle.

In a CLCA including either the previous or the subsequent occupation life cycle, allocation is avoided through system expansion and the resulting model is the same as that described in this paper.

5.2 Use of terminology for other resources

The differentiation of primary, secondary and tertiary impacts could be useful for the analysis of the cycling of other resources than land within the technosphere. Primary impacts could refer to the impacts associated with the material substance per se in various life cycle stages, e.g. impact of water (which depends on its environmental quality) and the impact of copper, which depends on its form and speciation. Secondary impacts relate to those associated with the 'waste management' life cycle per se, e.g. the life cycle impacts of the wastewater treatment plant or of copper recycling processes. Finally, tertiary impacts refer to the disruptions in the use and transformation of other substitutable materials in the technosphere, e.g. affected water treatment plants if the wastewater is recycled, and affected extraction, transformation, recycling and landfilling of copper (and possibly other materials) in other life cycles.

5.3 The need for a case study

The model complexity introduced by including tertiary impacts within the scope of brownfield rehabilitation LCA is justified only if these impacts are significant. Quantitative case studies are needed to evaluate the magnitude of tertiary impacts relative to primary and secondary impacts. Part II of this paper presents such a case study for a contaminated urban brownfield rehabilitated for residential redevelopment.

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